

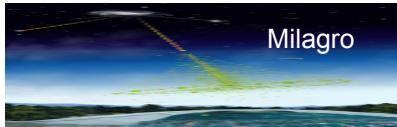


Surveying the TeV Sky with Milagro

Curtis Lansdell
University of Maryland
For the Milagro Collaboration

Outline

- Description of Milagro
- Background rejection technique
- TeV survey for point sources
- Detection of the galactic plane
- TeV survey for extended sources
- TeV emission from GRBs
- Future detector based on Milagro



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Current Milagro Collaboration -7/05



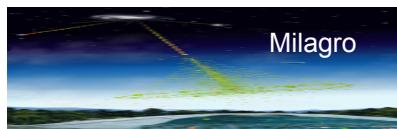
- Los Alamos – S. Casanova, B. Dingus, G. Sinnis, G. Walker
- Maryland – D. Berley, R. Ellsworth⁺, J. Goodman, C. Lansdell, J. McEnery*, D. Noyes, A. Smith, V. Vasileiou
- U.C. Santa Cruz – D. Coyne, P. Saz Parkinson, D. Williams, L. Yang
- U.C. Irvine – B. Allen, T. Shoup, G. Yodh
- NYU – B. Kolterman, A. Mincer, P. Nemethy
- Michigan State – A. Abdo, J. Linnemann
- U. New Hampshire – J. Ryan



*at GSFC, ⁺at George Mason University



10 (2) Faculty (Retired), 6 Students, 3 Research Scientists, 4 Post-docs

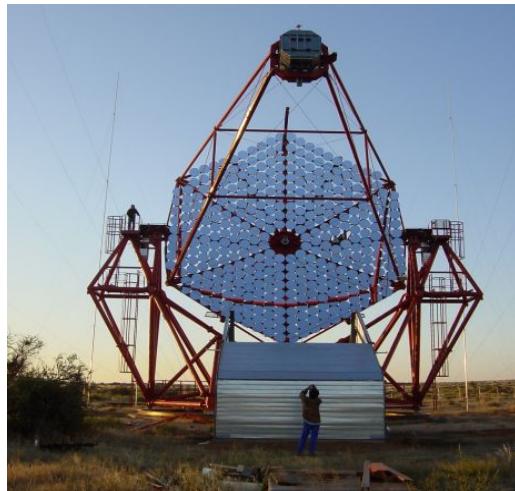


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Detectors in Gamma-Ray Astrophysics

High Sensitivity

HESS, MAGIC, CANGAROO, VERITAS



Large Effective Area

Excellent Background Rejection (>99%)

Low Duty Cycle/Small Aperture

High Resolution Energy Spectra

Studies of known sources

Surveys of limited regions of sky

Point source sensitivity

Low Energy Threshold

EGRET/GLAST



Space-based (small area)

“Background Free”

Large Duty Cycle/Large Aperture

Sky Survey (<10 GeV)

AGN Physics

Transients (GRBs) <100 GeV

Large Aperture/High Duty Cycle

Milagro, Tibet, ARGO, HAWC?



Moderate Area/Large Area (HAWC)

Good Background Rejection

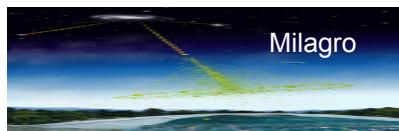
Large Duty Cycle/Large Aperture

Unbiased Sky Survey

Extended sources

Solar physics/space weather

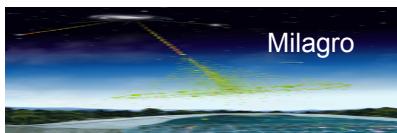
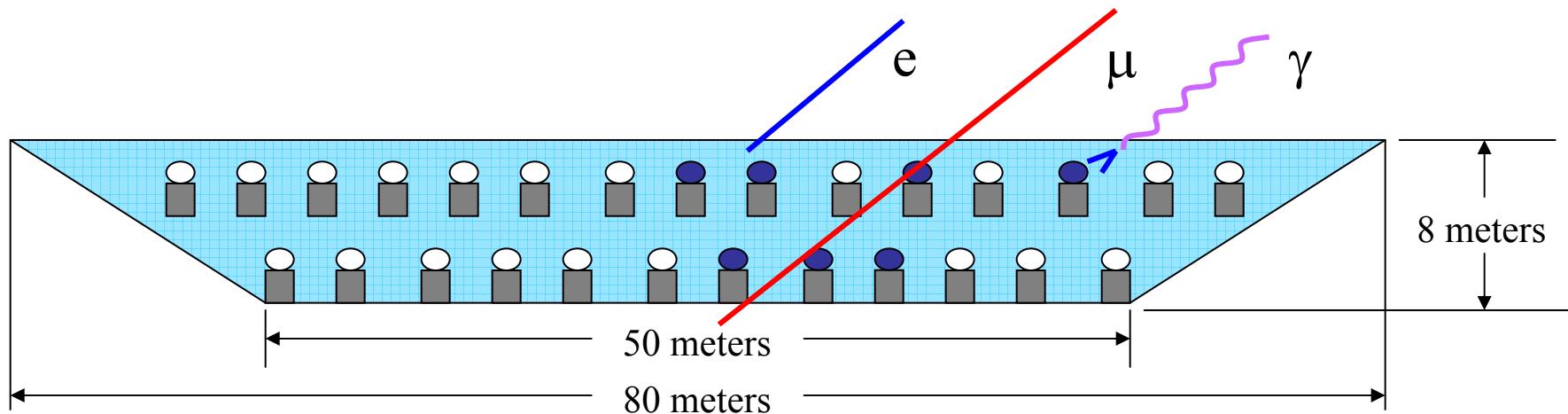
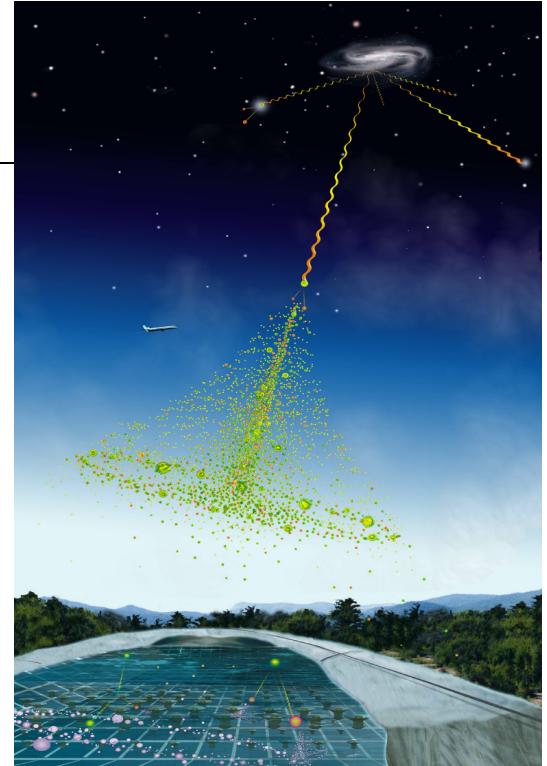
Transients (GRBs, AGNs)



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How Does Milagro Work?

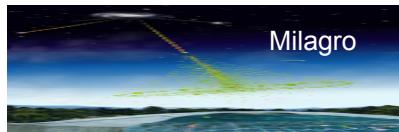
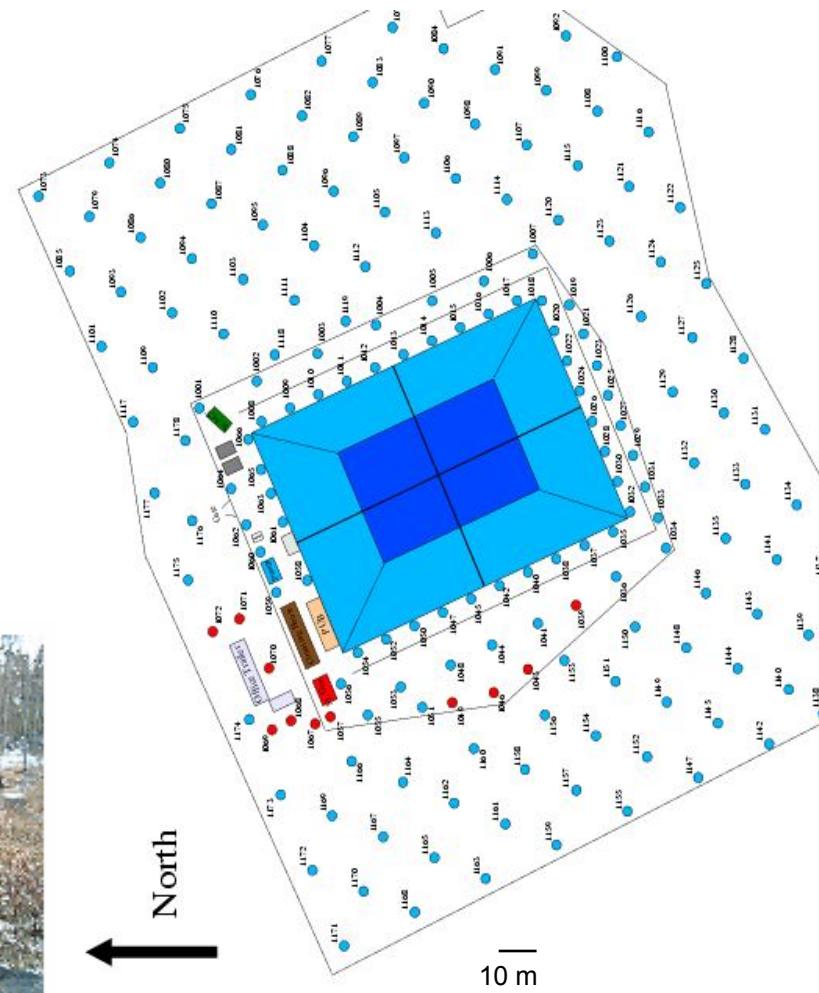
- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 6m pond containing filtered water
- Reconstruct shower direction to $\sim 0.5^\circ$ from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is $\sim 2 \text{ sr}$ and the average duty factor is $>90\%$



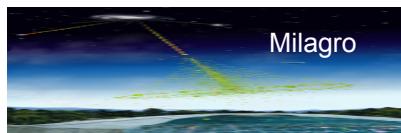
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The Milagro Detector

- 2630m asl
- Water Cherenkov Detector
- 898 detectors
 - 450(t)/273(b) in pond
 - 175 water tanks
- $3.4 \times 10^4 \text{ m}^2$ (phys. area)
- 1700 Hz trigger rate
- $\sim 0.5^\circ$ resolution
- > 90% proton rejection



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Under the Cover

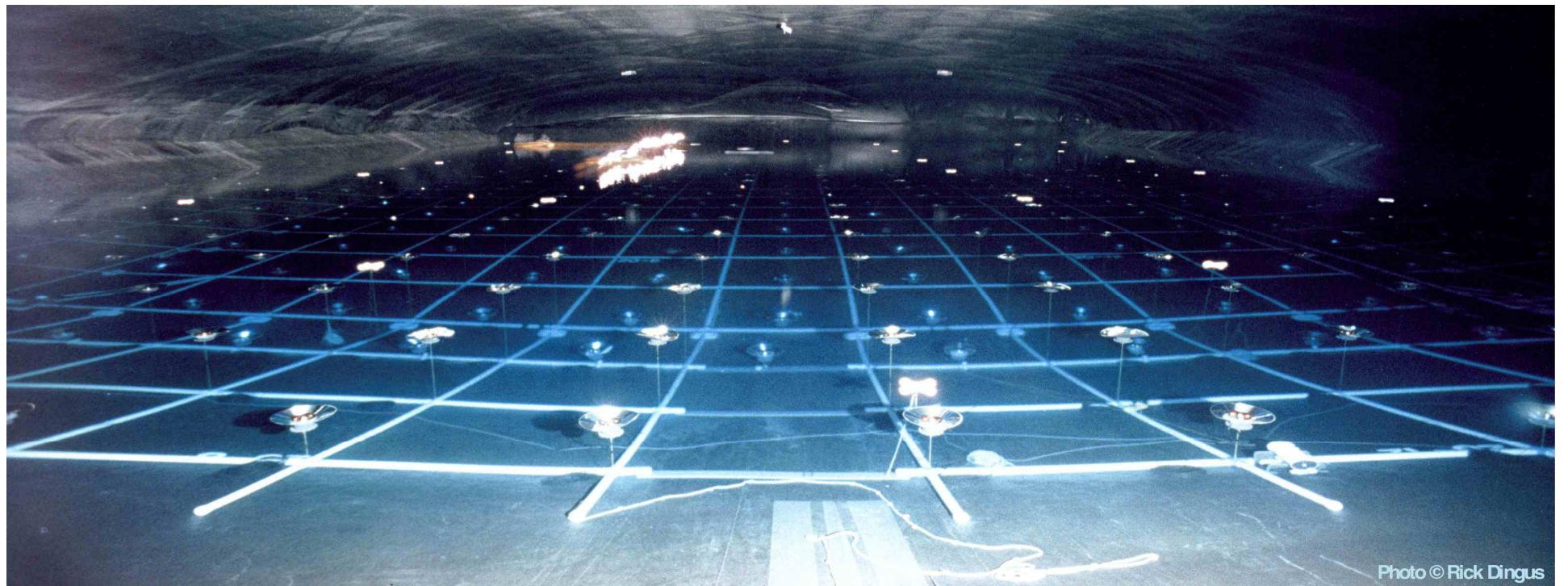
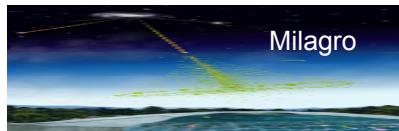


Photo © Rick Dingus

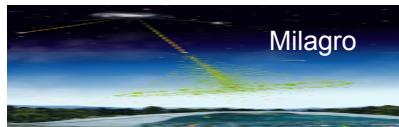


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Timeline/Operation

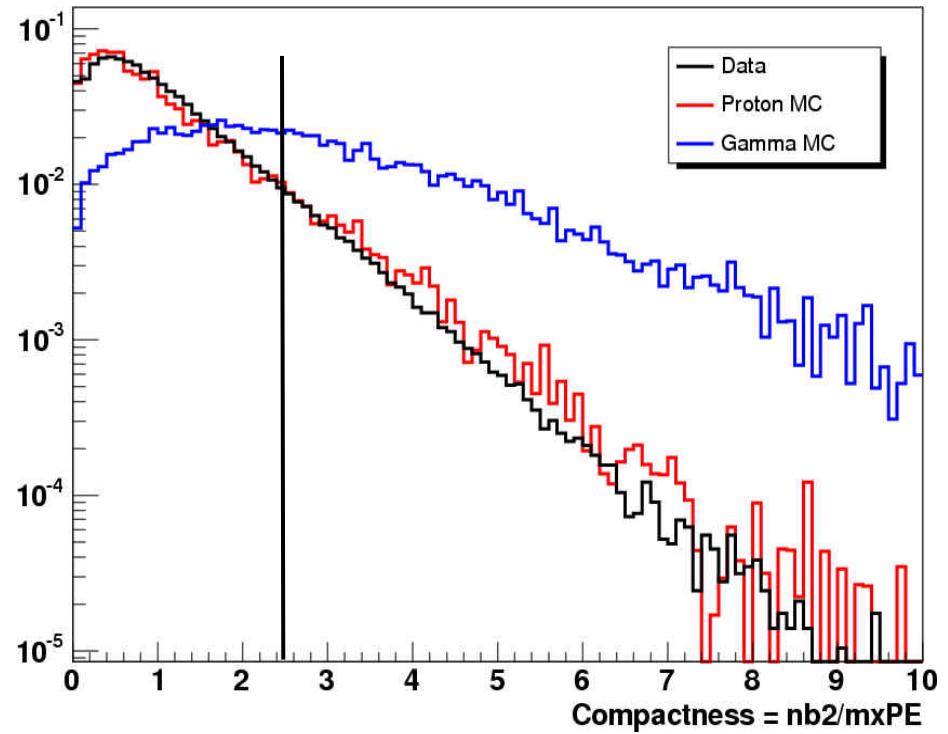
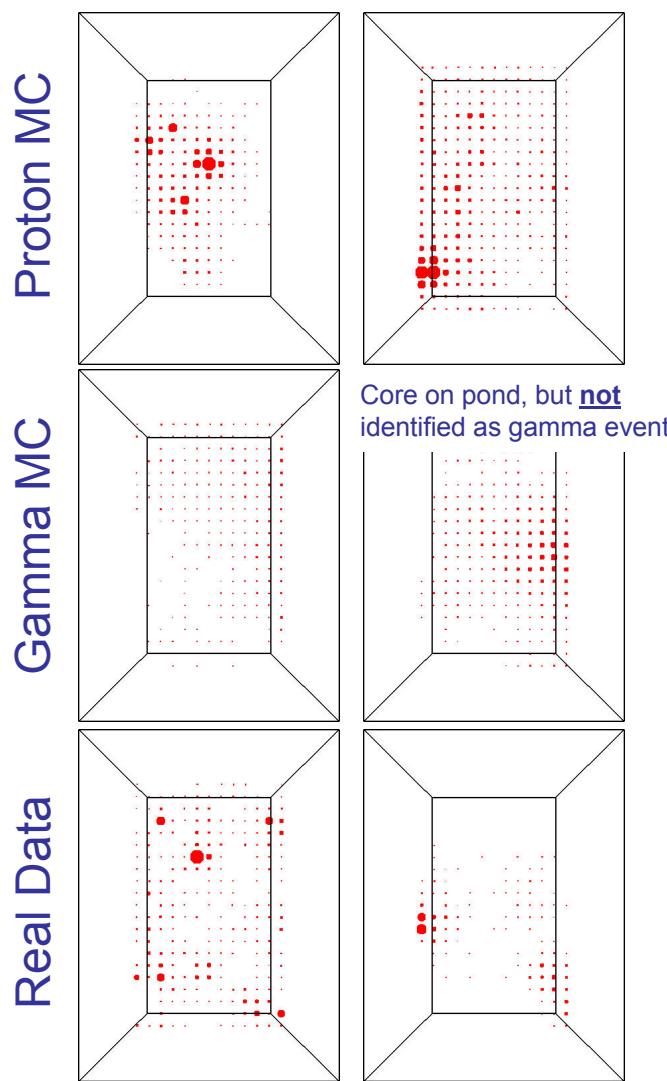
Fall 1999	- Installed PMTs
Summer 2000	- Began data taking, first “usable data”
January 2001	- Science data begins
Summer 2002	- Installed threshold lowering GRB trigger - Began construction of outrigger array
Spring 2003	- Completed outrigger array
Summer 2004	- Completed calibration system for outrigger array

- 6 MB/s DC data rate → ~100 TB of raw data/yr
- Use online reconstruction for sky surveys



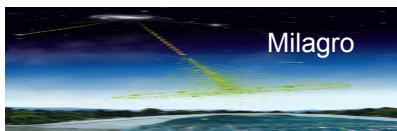
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γ/h Separation



$$C = \frac{NBottom(>2PEs)}{PE_{max}(Bottom)}$$

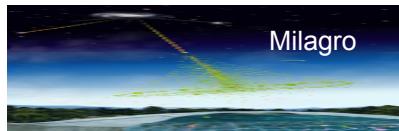
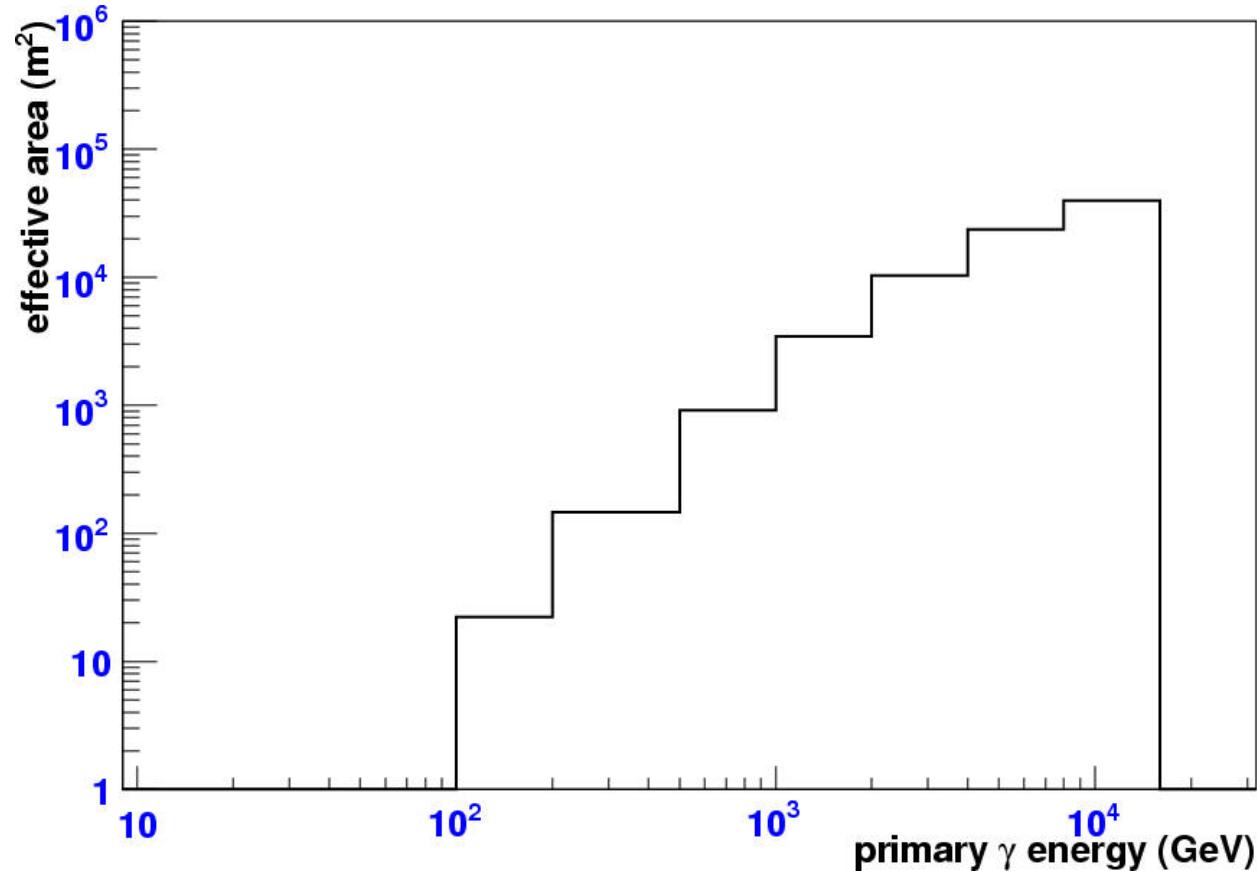
Retains 50% γ s and 9% protons,
 $Q = \varepsilon_\gamma / \sqrt{\varepsilon_h} = 1.6$



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Effective Area

Median γ -ray energy assuming Crab spectrum is 3 TeV.



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Point Source Search

Bin Size = 2.1°

4.5 years of data

Crab significance

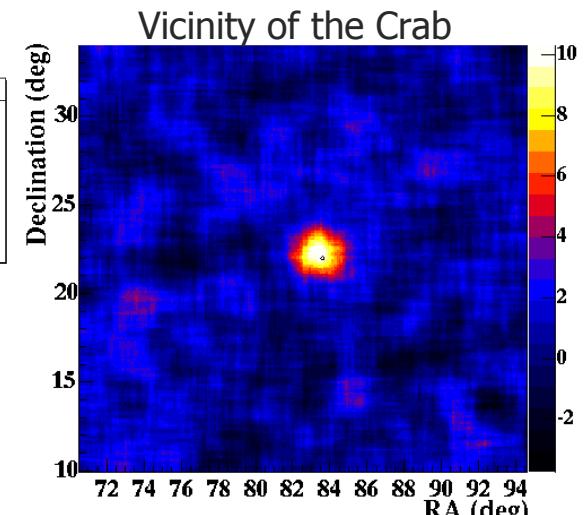
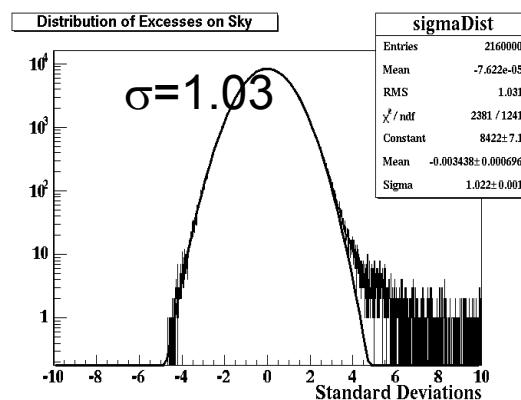
Mrk421 significance

Point in Cygnus Region at

10.0σ

5.4σ

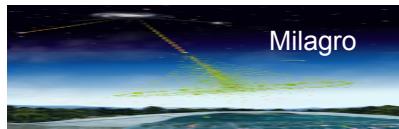
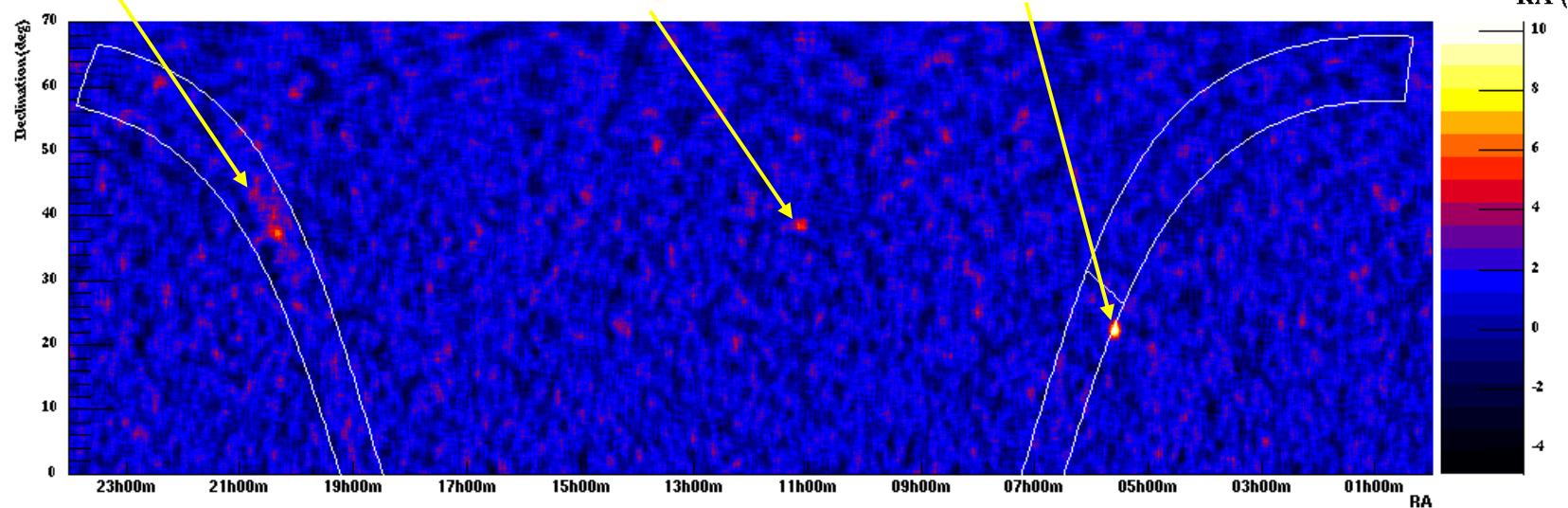
5.9σ



Cygnus Region

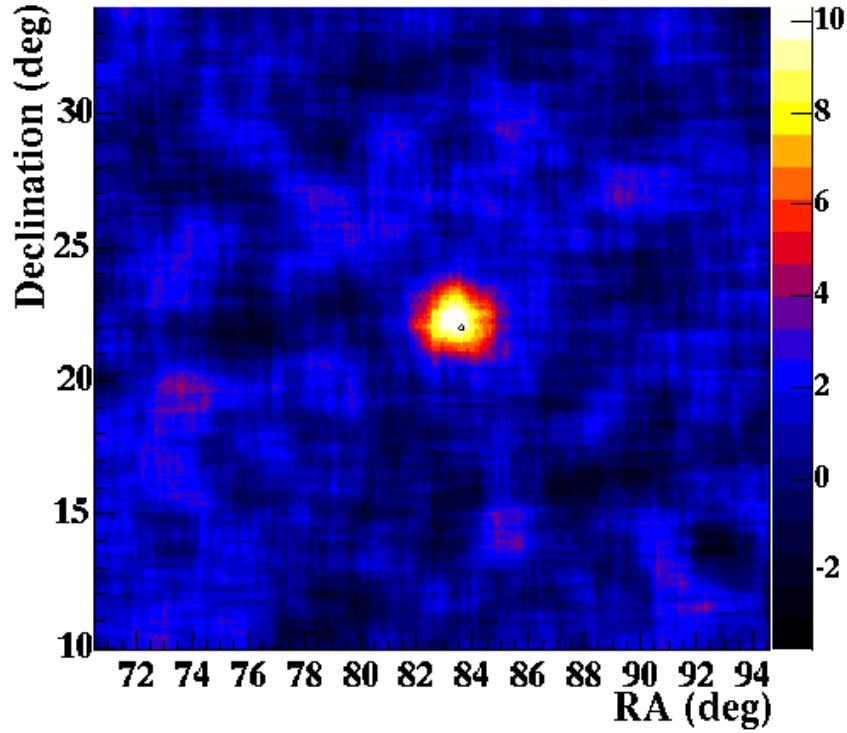
Mrk421

Crab



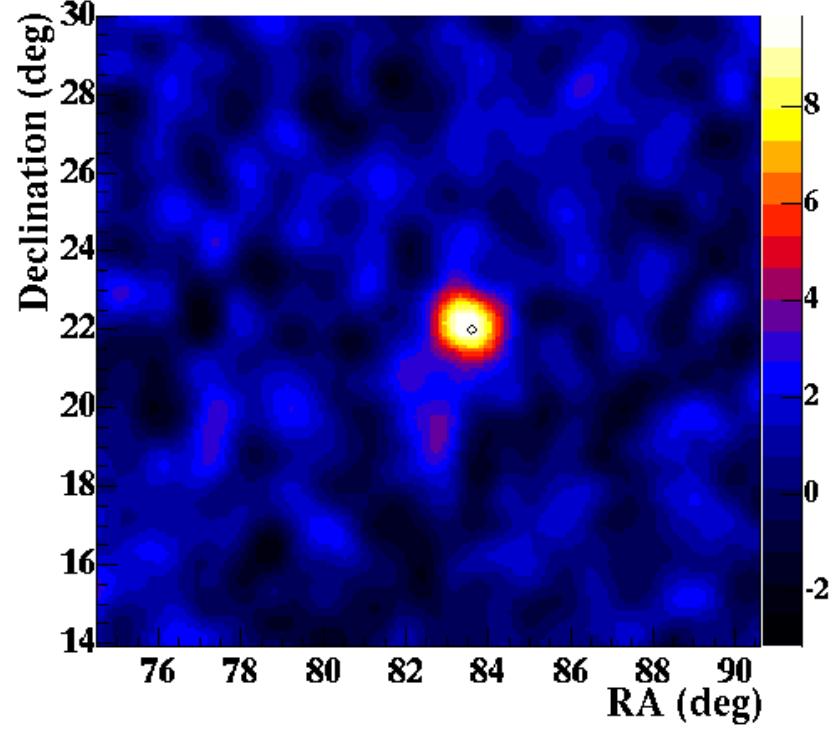
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Sensitivity of Milagro to VHE Point Sources



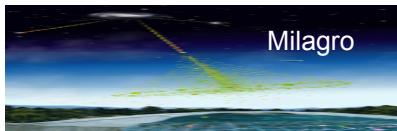
Pre-Outrigger – data since 2000

- Optimized with MC simulations
- Published detection of the Crab (*ApJ* 595, 803 (2003))
- Sensitivity: $\sim 4.7\sigma/\text{yr}$ on the Crab
- **10.0σ in 4.5 years**



Post-Outrigger – data since 2003

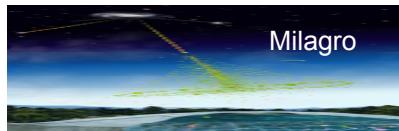
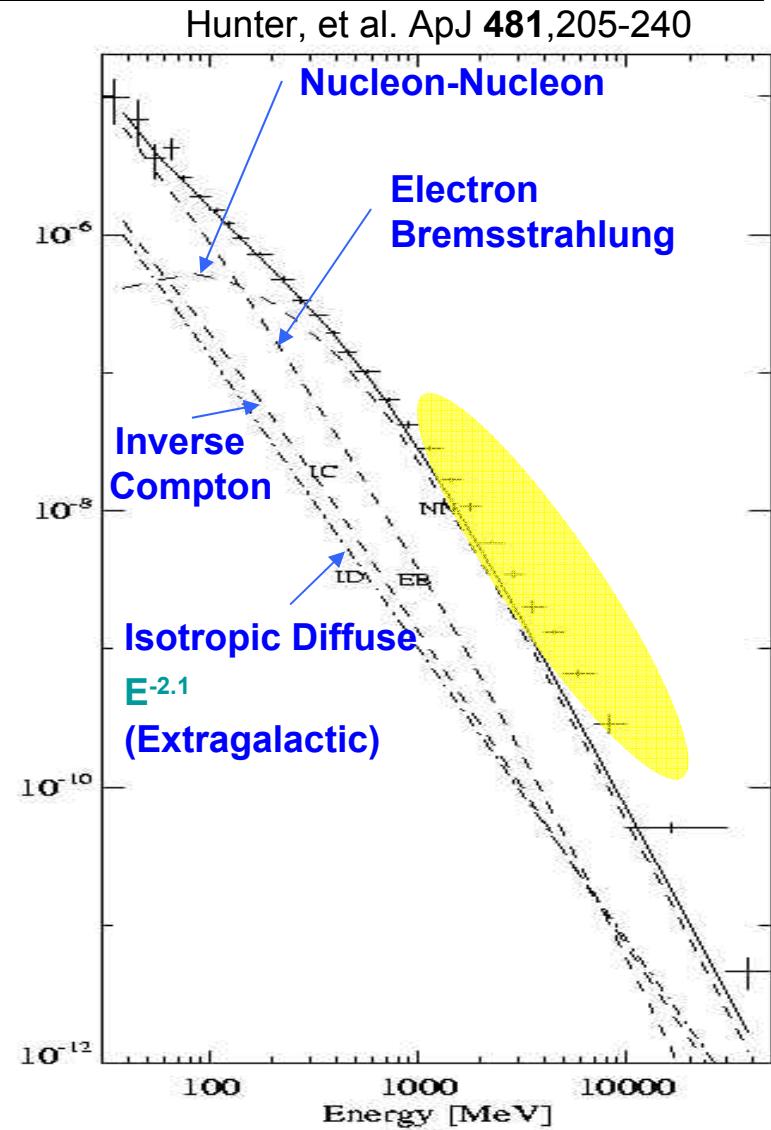
- Good angular reconstruction on off-pond cores
- Sensitivity: $\sim 8\sigma/\text{yr}$ on the Crab
- **9.7σ in 1.5 years**



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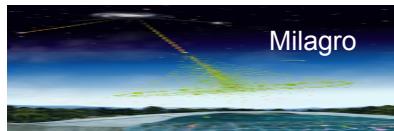
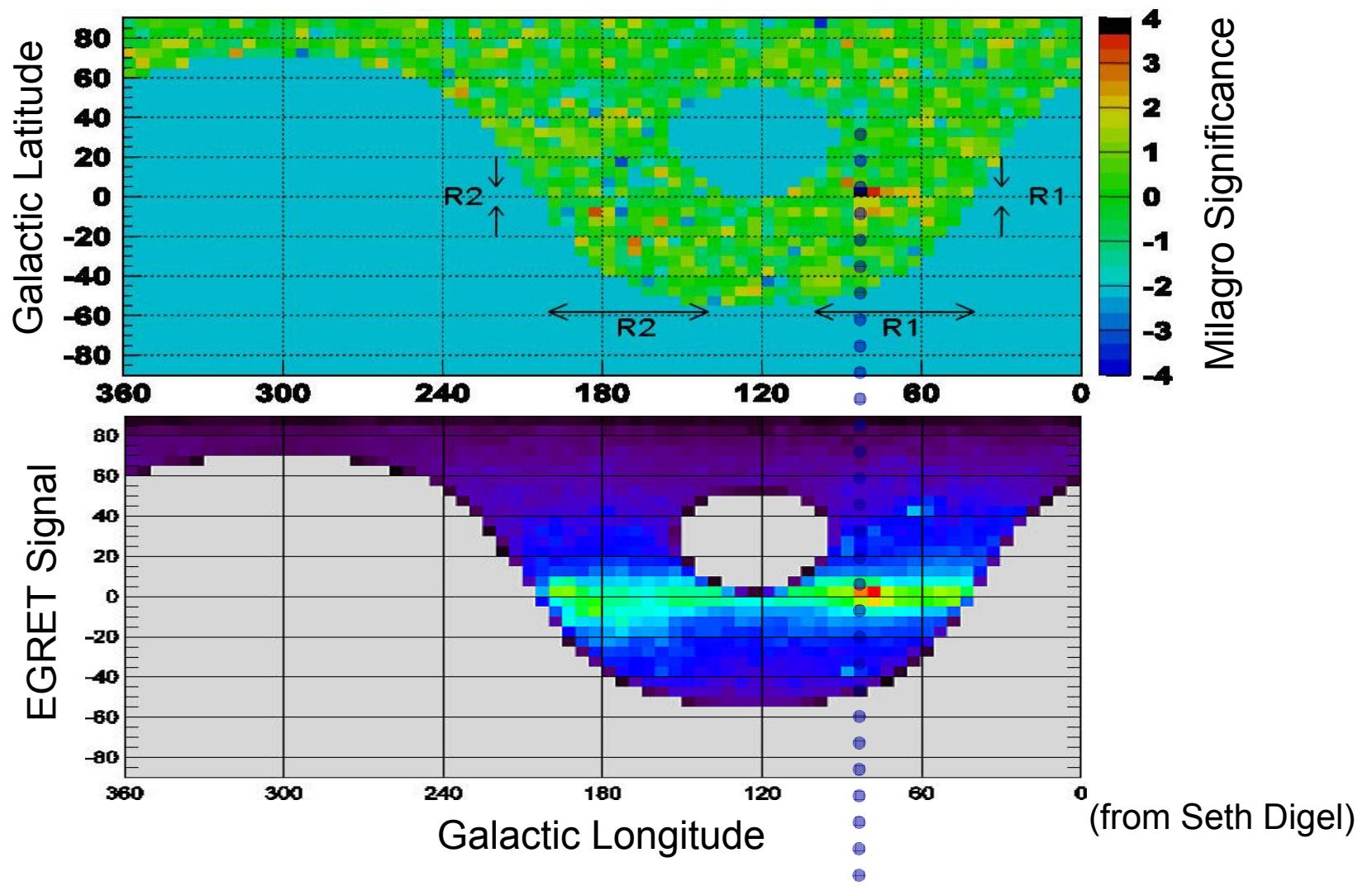
Galactic Plane Excess

- EGRET measured Galactic diffuse spectrum in $|b|<10$ and $300<|l|<60$
- Still sees excess in flux >1 GeV
 - Softer $E^{-2.4}$ spectrum
- Is there an excess in TeV range?



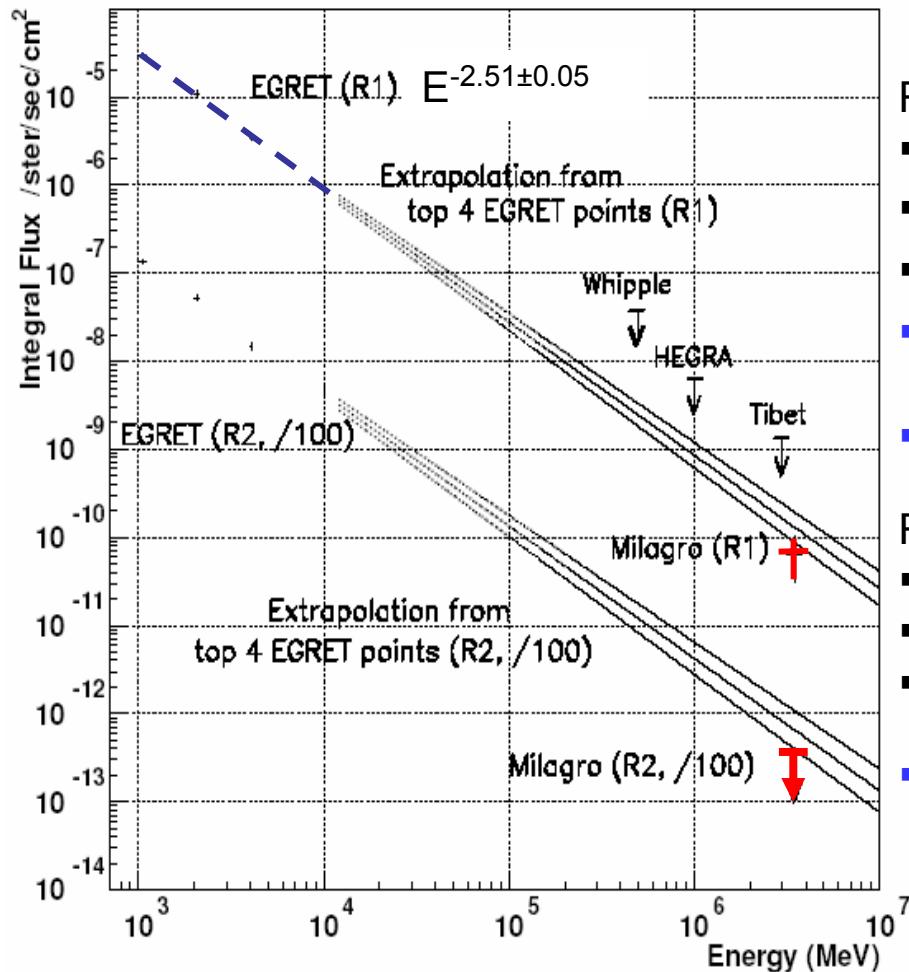
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Milagro Results: 3 Year Exposure



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Integral Flux: Milagro & EGRET



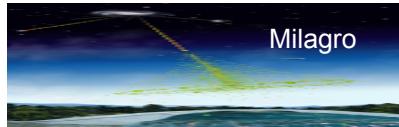
A priori cuts, based on 3yr of data, 4.5 σ

R1

- Combined EGRET-Milagro fit
- Flux(>3.5 TeV) = $(6.8 \pm 1.5 \pm 2.2) \times 10^{-11} / \text{cm}^2/\text{s}/\text{sr}$
- Spectral Index = $-2.61 \pm 0.03 \pm 0.05$
- With outriggers we can measure the spectrum at TeV energies
- 2 more years of data needed for ± 0.1 on spectral index at TeV energies

R2

- Flux(>3.5 TeV) < $4 \times 10^{-11} / \text{cm}^2/\text{s}/\text{sr}$ (99% CL)
- Spectral index < -2.66 (99% CL)
- Not yet a crisis but spectrum may be softer in outer Galaxy
- Additional data will tell



Extended Source Search

Distribution of Excesses on Sky (Crab and Mrk 421 and Cygnus Region removed)

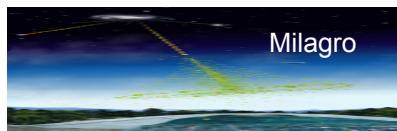
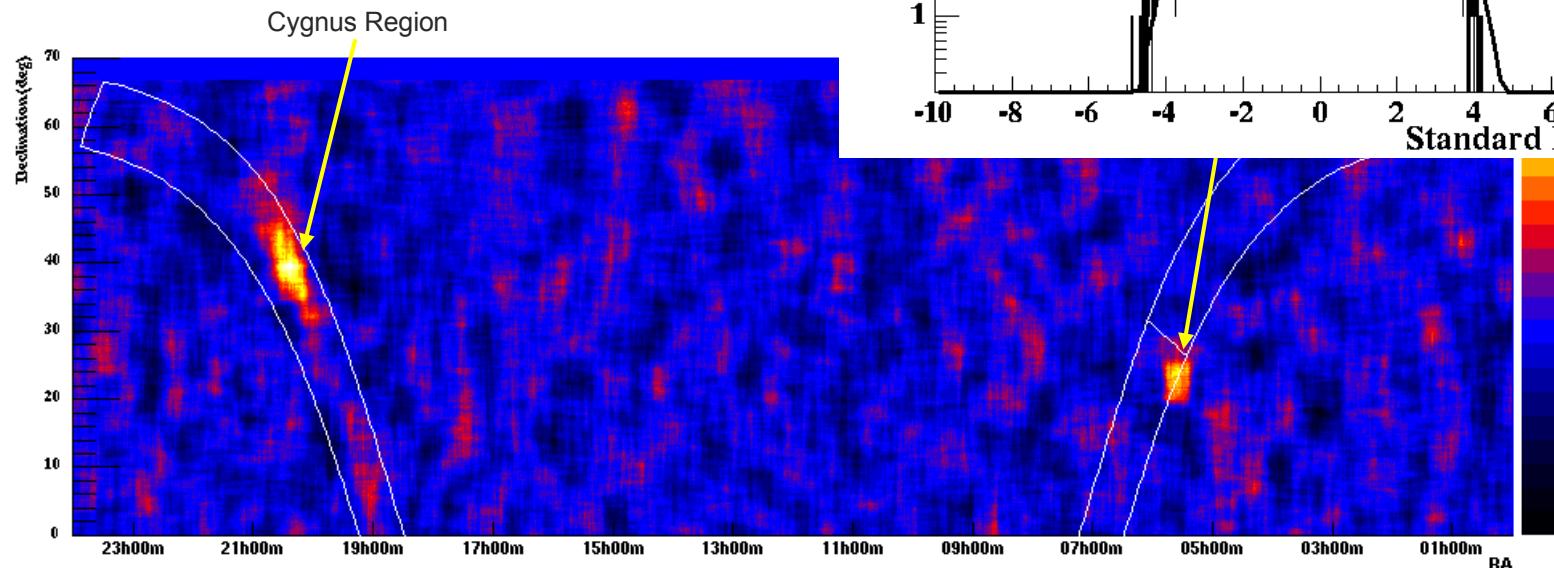
Bin Size = 5.9°

4.5 years of data

Cygnus Region Significance: 9.1σ

Post-trials probability: $>7\sigma$

Cygnus Region is the most luminous source of VHE γ -rays in the northern sky.



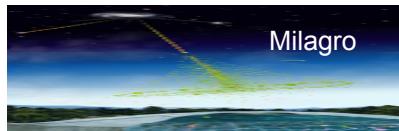
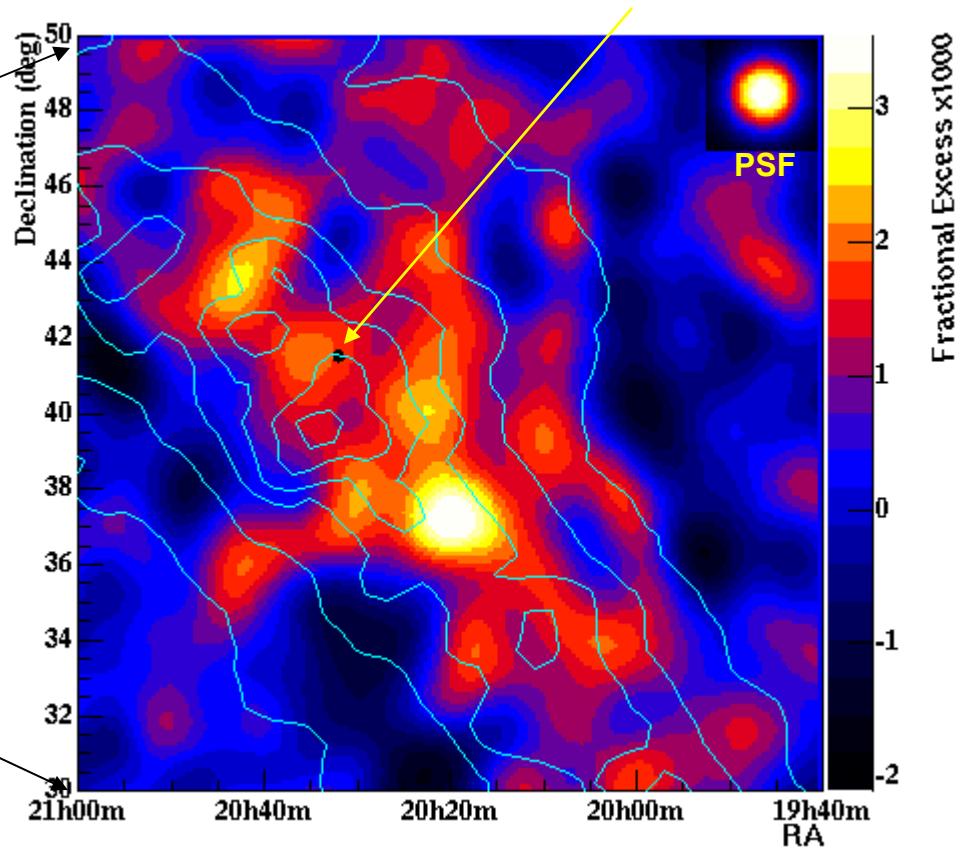
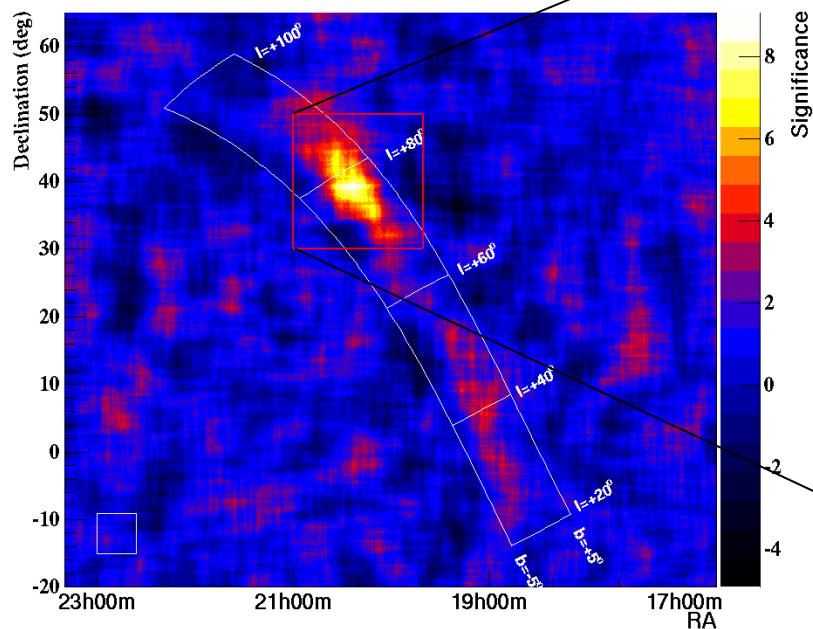
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Cygnus Region Morphology

- Convolve Cygnus Region excess with Milagro PSF (0.75°)
- Region shows resolvable structure

HEGRA detected TeV
Source: TEV J2032 4130

EGRET Diffuse Model



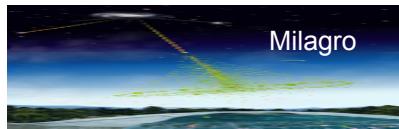
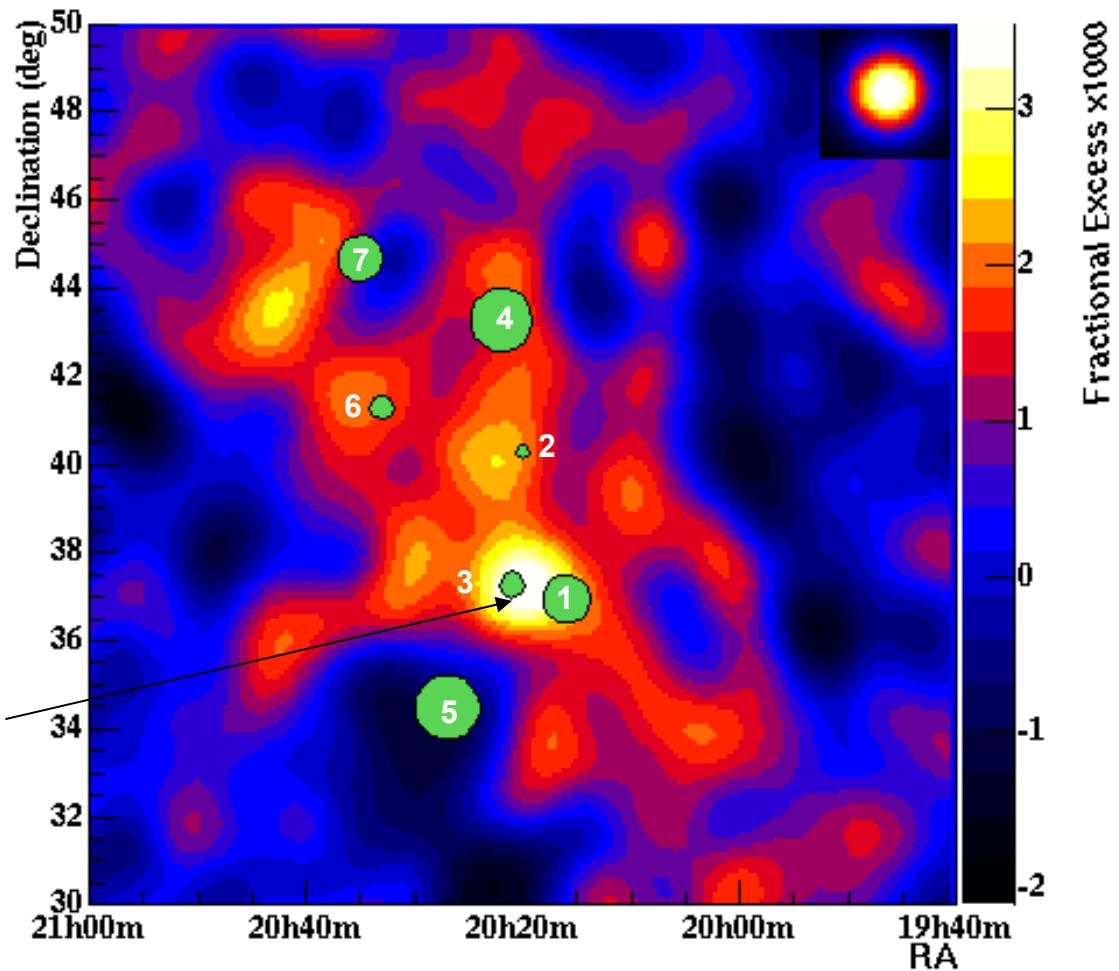
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EGRET Unidentified Sources in the Cygnus Region

		$\Phi > 100 \text{ MeV/cm}^2\text{s}$	γ
1	3EG J2016+3657	$(34.7 \pm 5.7) \times 10^{-8}$	2.09
2	3EG J2020+4017	$(123. \pm 6.7) \times 10^{-8}$	2.08
3	3EG J2021+3716	$(59.1 \pm 6.2) \times 10^{-8}$	1.86
4	3EG J2022+4317	$(24.7 \pm 5.2) \times 10^{-8}$	2.31
5	3EG J2027+3429	$(25.9 \pm 4.7) \times 10^{-8}$	2.28
6	3EG J2033+4118	$(73.0 \pm 6.7) \times 10^{-8}$	1.96
7	3EG J2035+4441	$(29.2 \pm 5.5) \times 10^{-8}$	2.08

3rd EGRET Catalog sources
shown with 95% position
error circle.

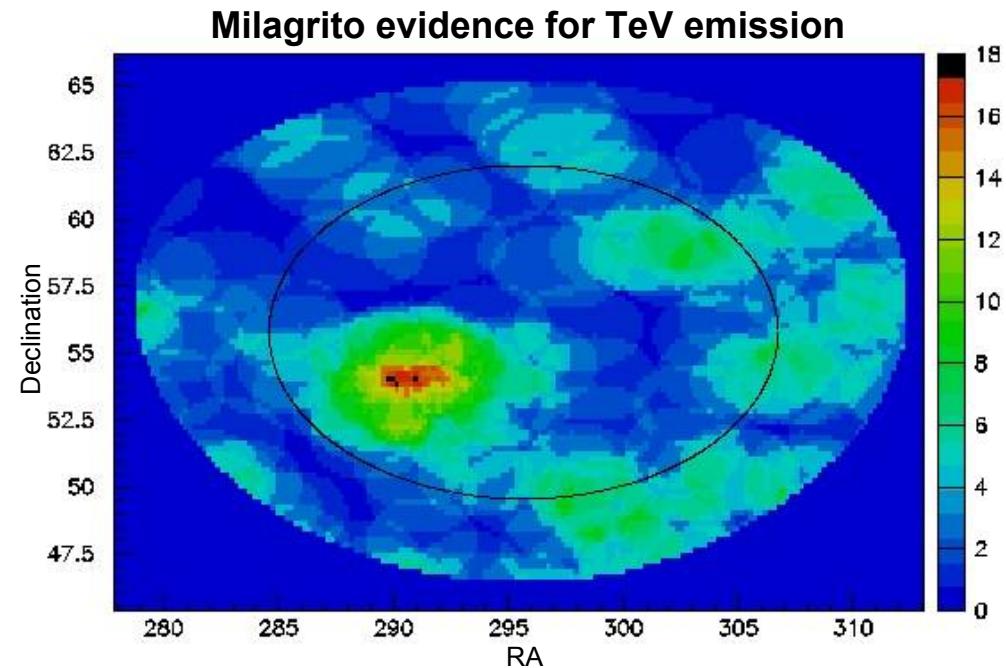
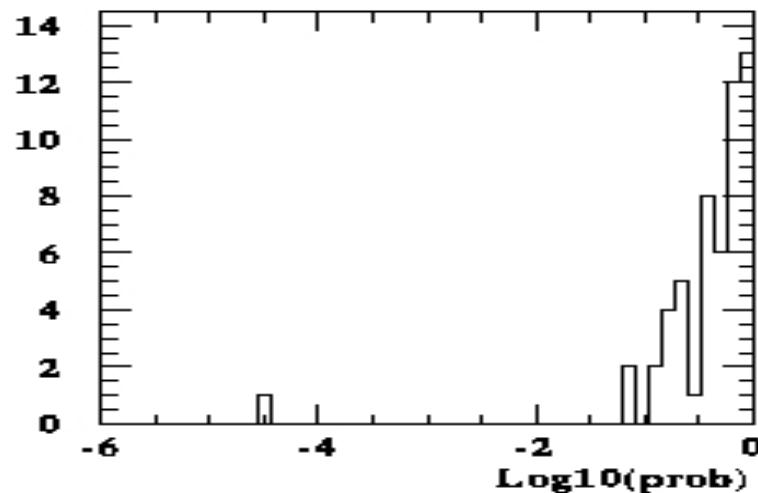
Flux of maximum point: 500mCrab
(May be extended)



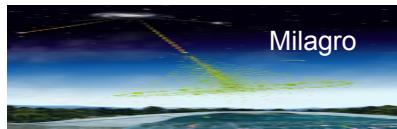
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Satellite Detected GRBs in Milagro's FoV

- Milagrito: prototype ran from 1997-1998, detected 1 out of 54 GRBs



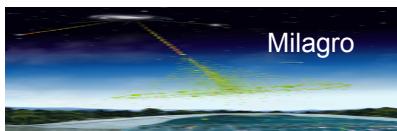
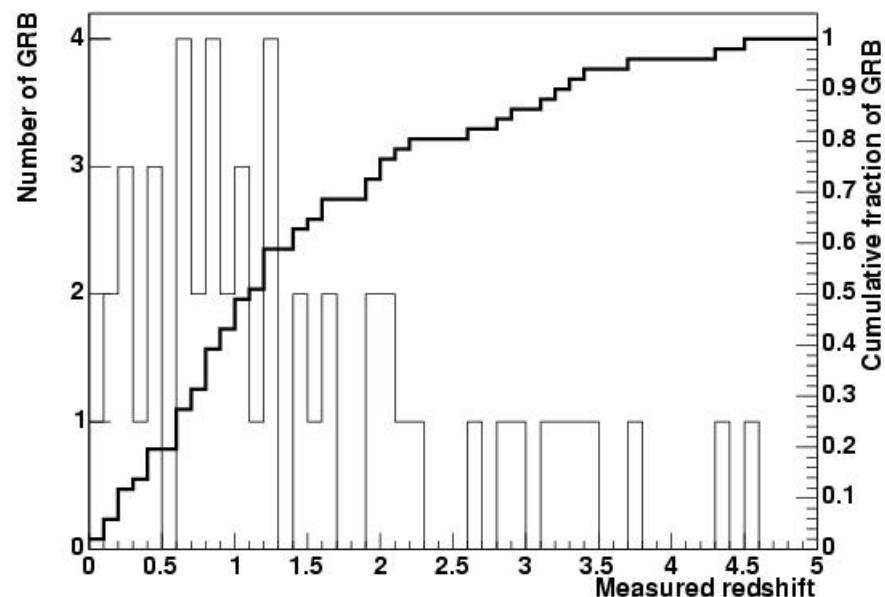
1 of 54 BATSE bursts searched. The Milagro sample of bursts is still smaller than the sample Milagrito had. GRB 970417a had a post-trial probability of 1.5×10^{-3} (including the 54 bursts searched).



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GRBs in Milagro

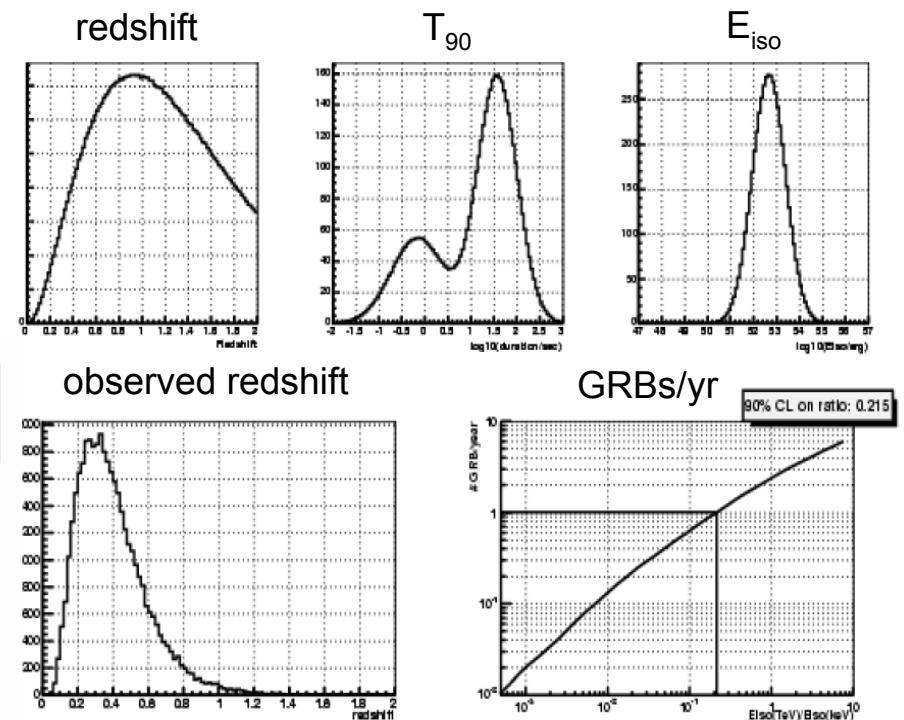
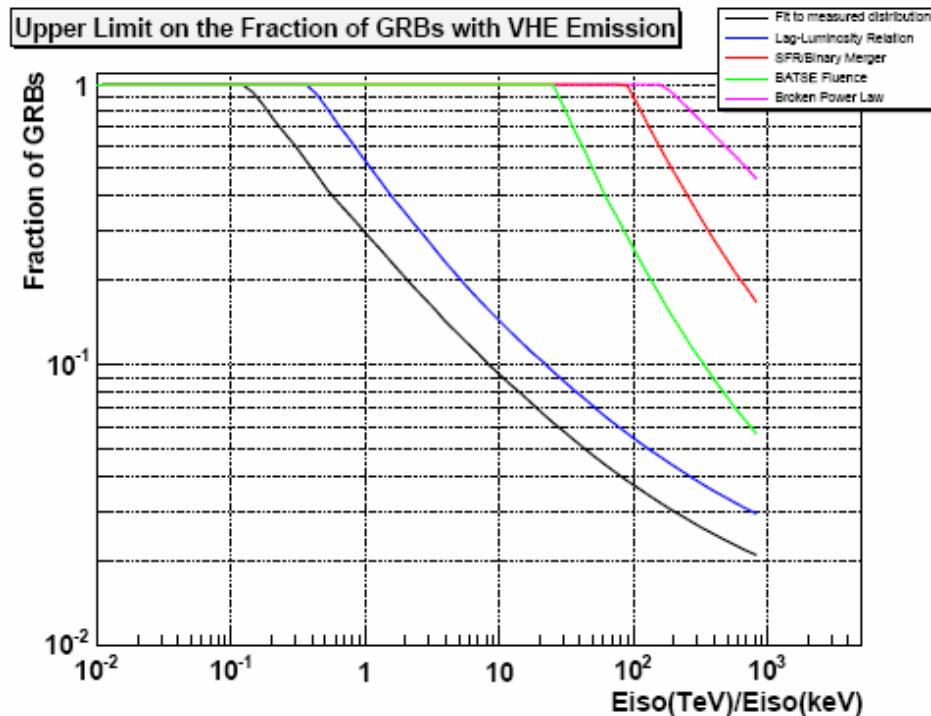
- Have not had such a burst during Milagro running
 - Searched 52 GRBs for TeV emission
 - 10 GRBs with known redshifts and 1 with redshift<0.5
- New SWIFT data should increase the rate to ~20 GRBs/yr (from ~4/yr) in Milagro FoV
- Most bursts are at high redshift
- $\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^-$,
so TeV gamma-rays are absorbed
at high redshift
 - Difficult to see most GRBs, want
redshift<0.5 and in Milagro's FoV
- Searching 3 years of Milagro data
for short duration transients
constrains VHE emission from
GRBs, but is model dependent



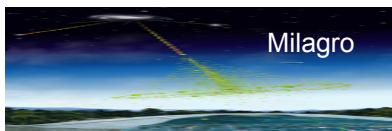
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Constraining GRB models

- Redshift dependence
- EBL model dependence
- Fluence dependence



Conclusion: Milagro can set model-dependent upper limits on the VHE emission from GRBs.





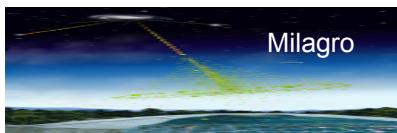
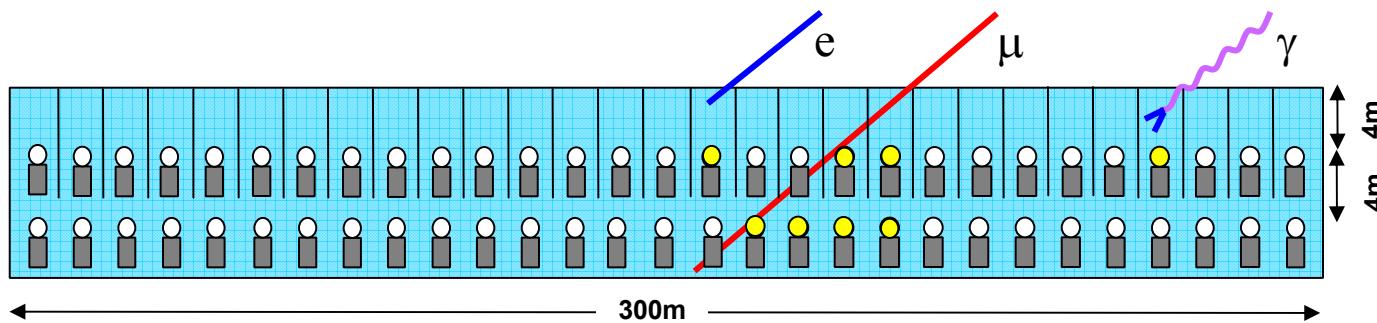
**HIGH
ALTITUDE
WATER
CHERENKOV
experiment**

Increase Altitude → Lower threshold

Increase Area → Better fitting (lever arm)
→ Better γ/h separation

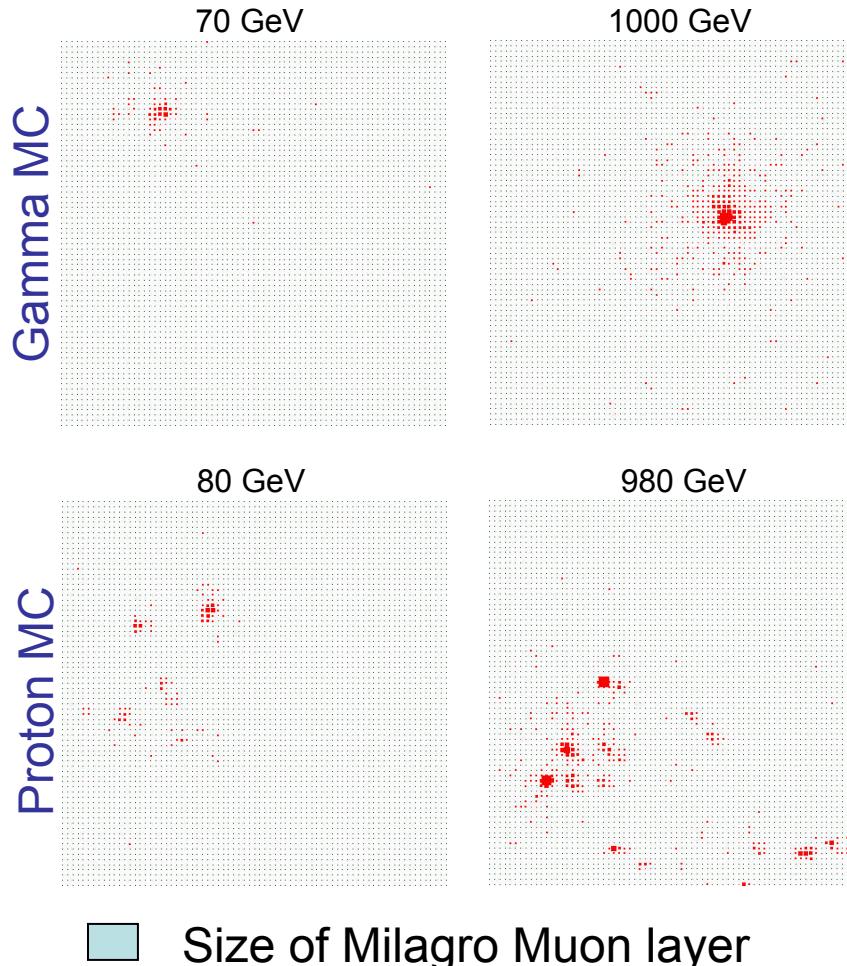
Optical Isolation → Containment of Muon light - Triggering

- 11250 PMTs
- Median energy ~ 300 GeV



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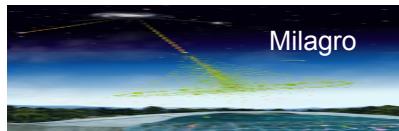
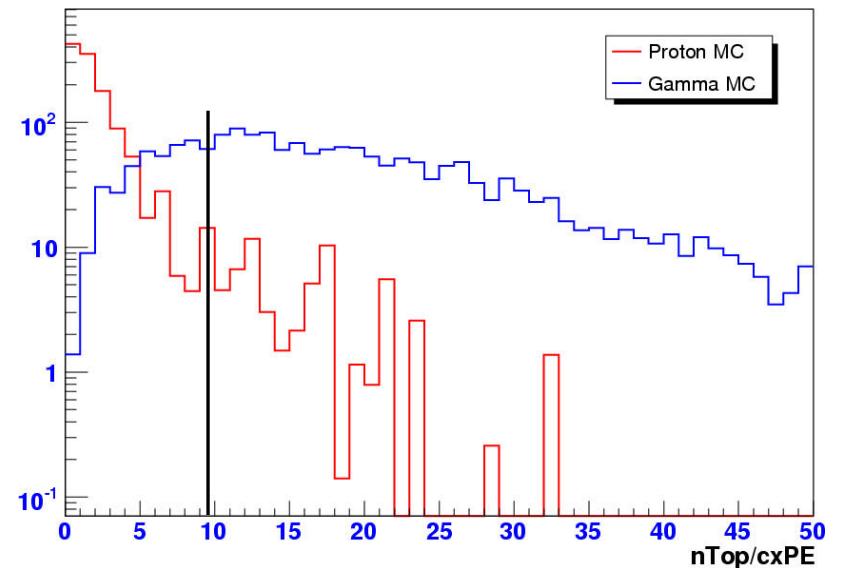
γ/h Separation with HAWC



Redefine Compactness:
Exclude large hits near the shower core

$C > 9.6$:
Reject 95% of hadrons, retain 78% γ s
 $Q = 3.5$

Median energy ~ 300 GeV

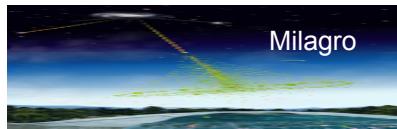
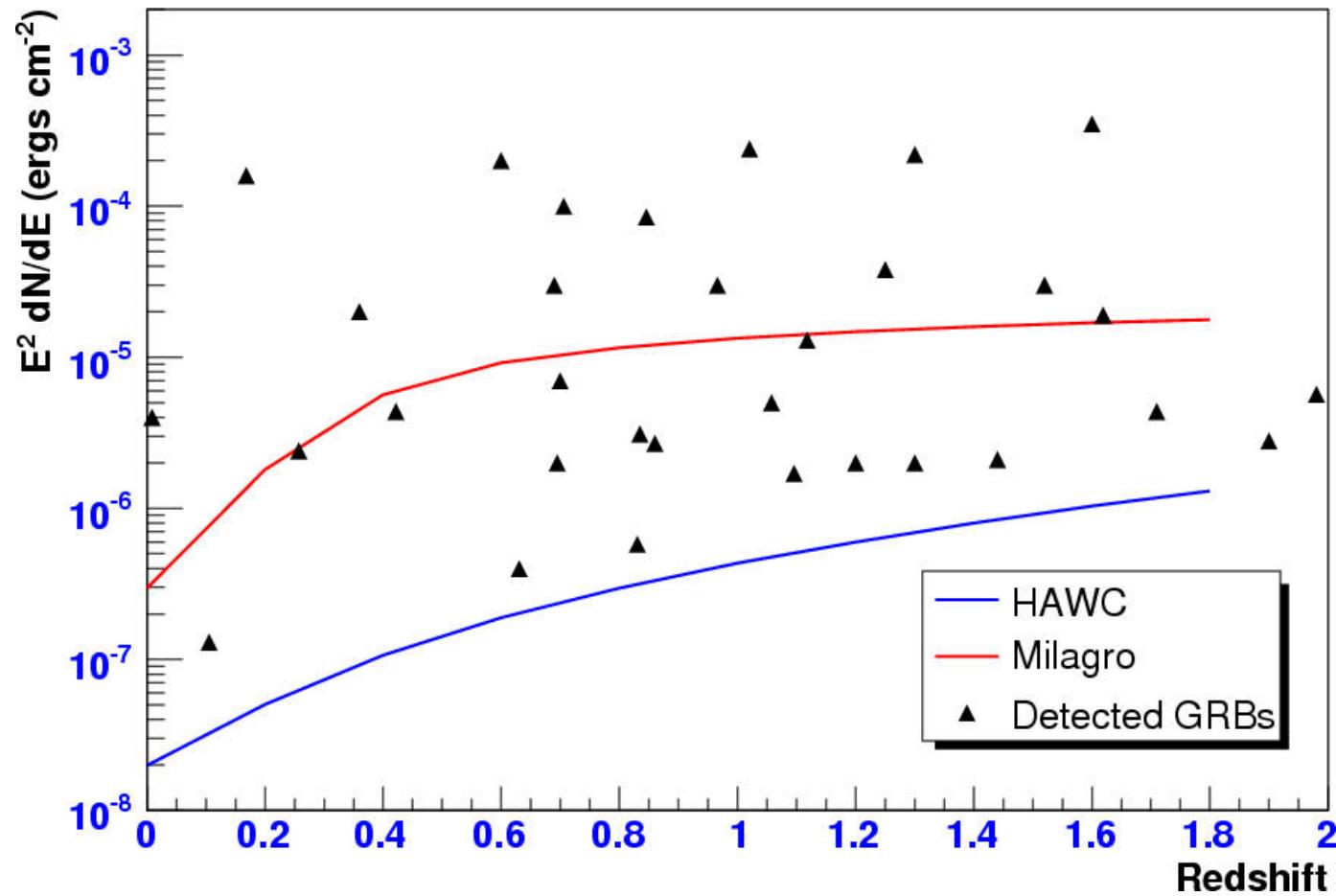


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100sec GRB Sensitivity vs Redshift

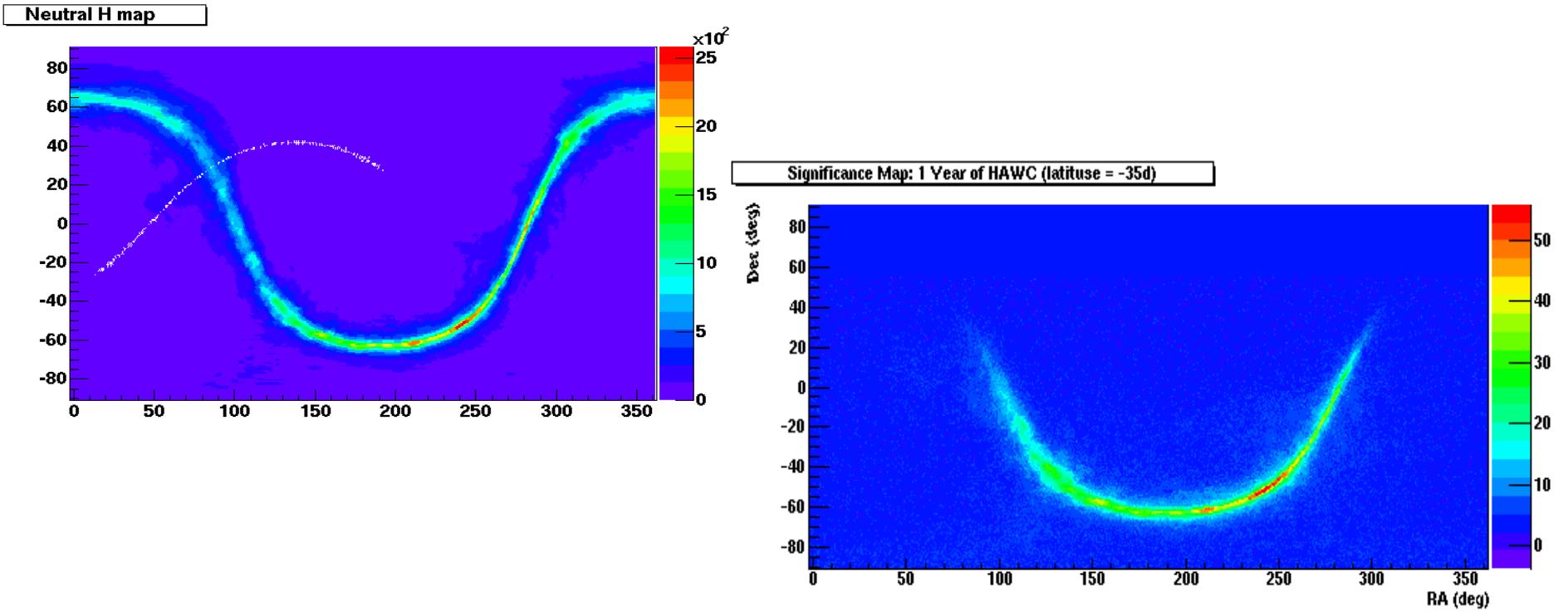
Sensitivity lines are for GRBs assumed to fall within 20° of zenith.

Comparing lines to data, assume GRBs have same fluence at TeV energies as at keV-MeV.



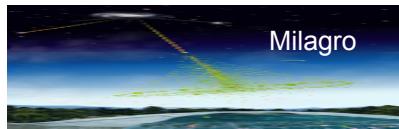
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Diffuse Galactic Plane in HAWC



Use Neutral H map to trace out VHE γ -ray flux. Normalize to Milagro observed TeV diffuse Galactic plane.

HAWC sees galactic plane at **~55 σ in 1 year**.



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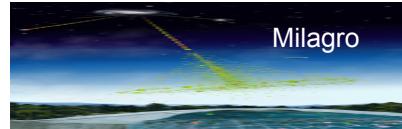
Conclusions

- Water Cherenkov method has not yet been fully exploited
 - Design improvements (Size, Altitude, ...) lead to much better than $\text{sqrt}(N)$ sensitivity improvements
 - HAWC $\sim 60x$ Milagro sensitivity
- Milagro TeV Survey
 - Crab Nebula at $8\sigma/\text{yr}$
 - Galactic Plane at 7.5σ in 4.5 years
 - Cygnus Region at 9.1σ in 4.5 years
 - Able to constrain VHE emission from GRBs
- Milagro's Future
 - Get energy spectrum of Galactic Plane to ± 0.1
 - Resolve hot spots in the Cygnus Region
 - Search for VHE GRB emission for ~ 20 SWIFT GRB/yr



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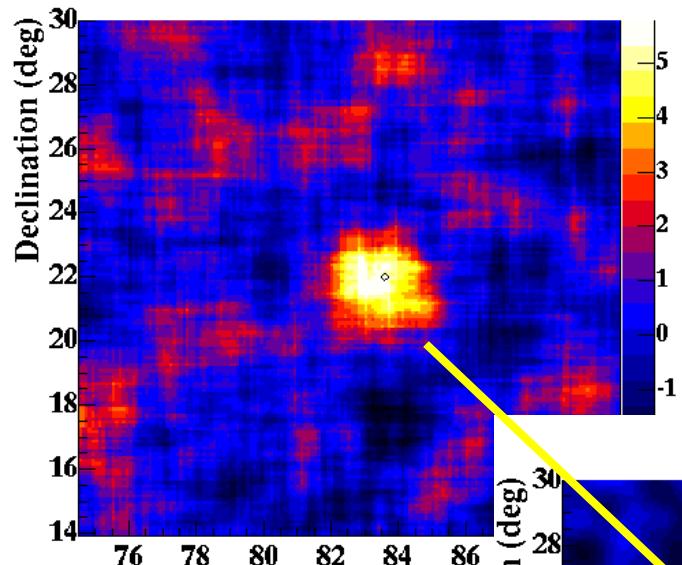
Extra Slides



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Crab in Milagro: Signal significance almost independent of cut level

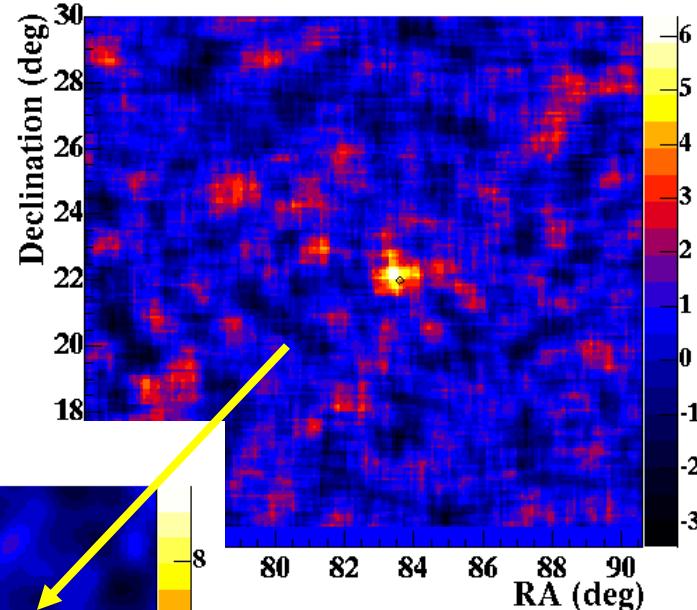
Std Cuts: $n\text{Fit} \geq 20, C > 2.5$



Excess = 5410, Off = 1218288,
 $\epsilon_{\text{hadron background}} \approx$

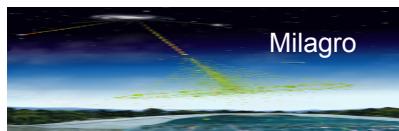
Weight events by
Expected S:B

Hard Cuts: $n\text{Fit} \geq 200, C > 6.0$



60, Off = 140, S:B = 1:2.3
on background $\approx 1 \times 10^{-5}$

1.5yr of data with outriggers



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Extended Source Sensitivity

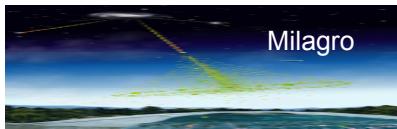
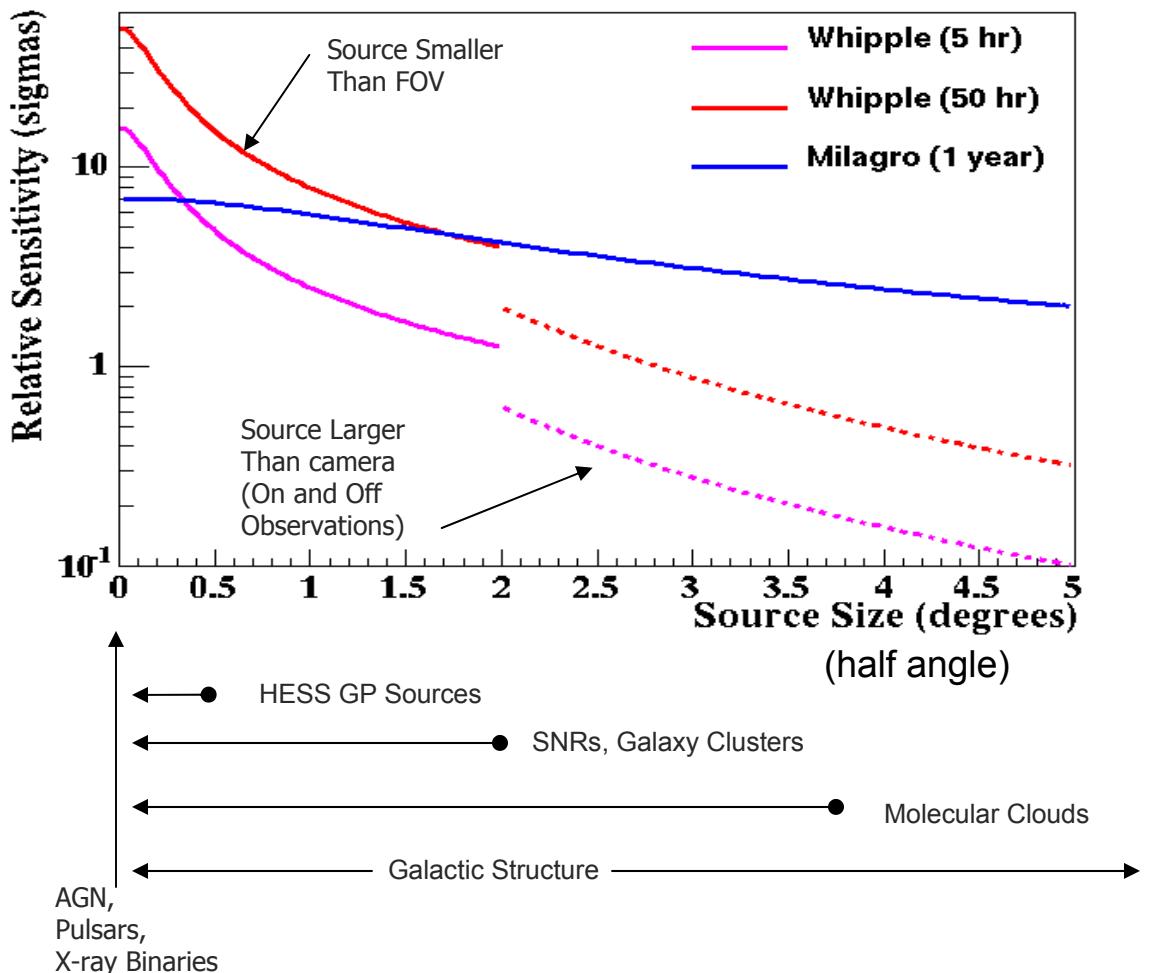
ACT's rely on angular resolution for excellent background rejection.

When the source size is large compared to PSF, sensitivity is reduced by a factor of

$$\sim \sigma_{\text{detector}} / \sigma_{\text{source}}$$

When the source size is large compared to the FOV, sensitivity is reduced by

$$\sim \sigma_{\text{detector}} / \sigma_{\text{source}}$$



Galactic Plane Excess

$-2^\circ < b < 2^\circ$

Consider Region $|l| = 20^\circ - 100^\circ$

Std Map: 5.0σ

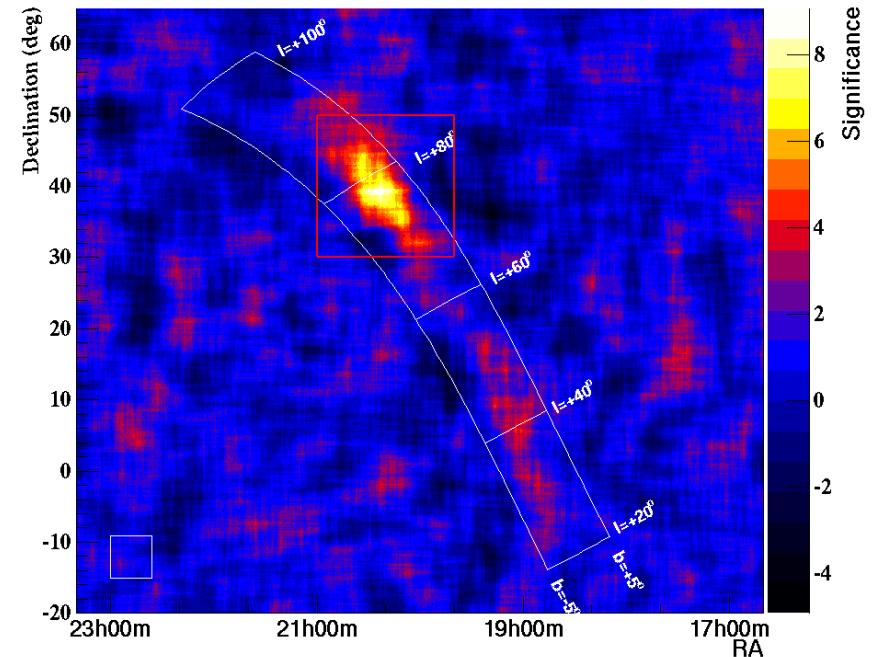
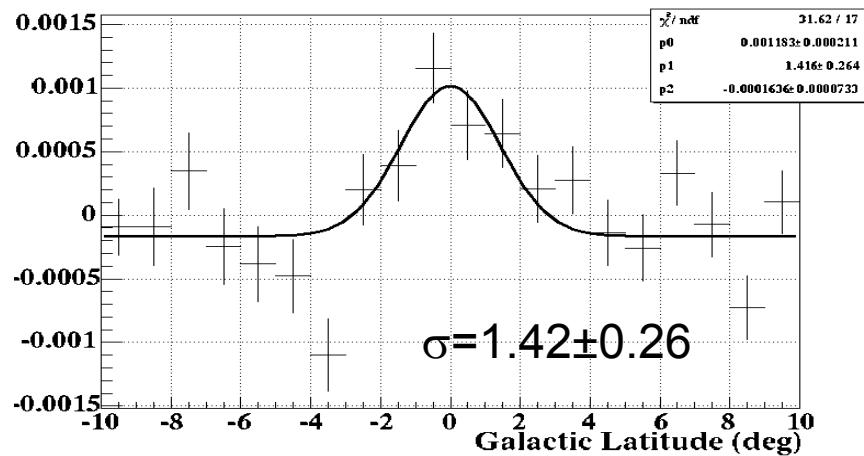
Weighted Map: 7.5σ

Exclude the Cygnus Region: $|l|=20^\circ - 75^\circ$

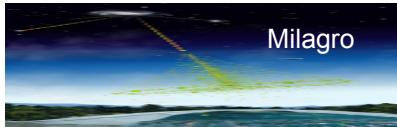
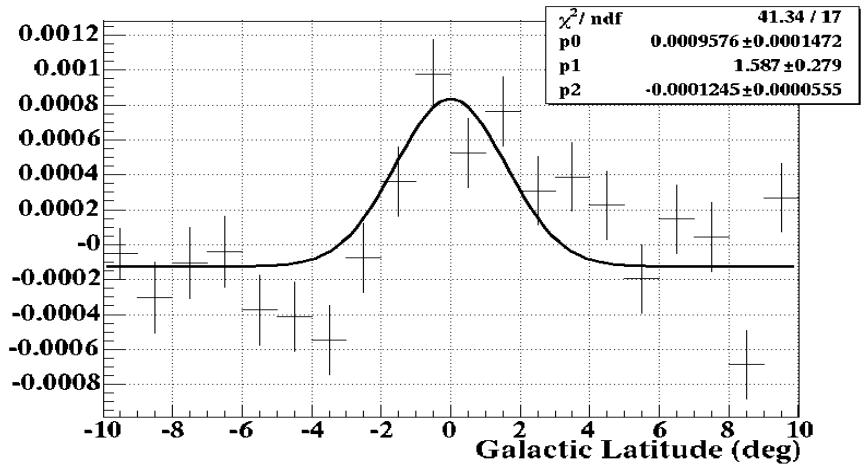
Std Map: 4.2σ

Weighted Map: 5.8σ

Galactic longitude 20-75 excludes Cygnus region



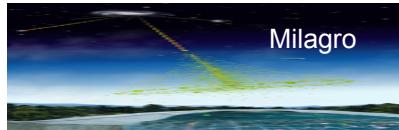
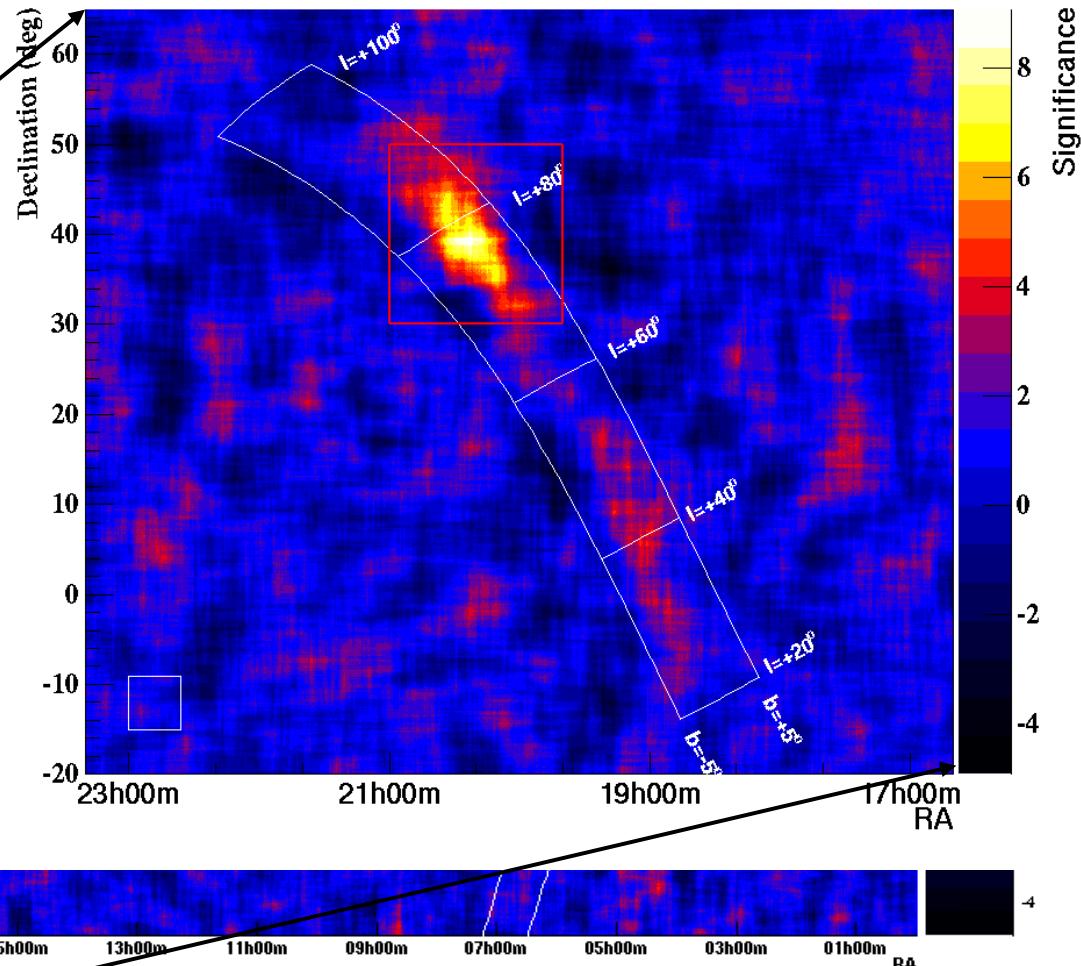
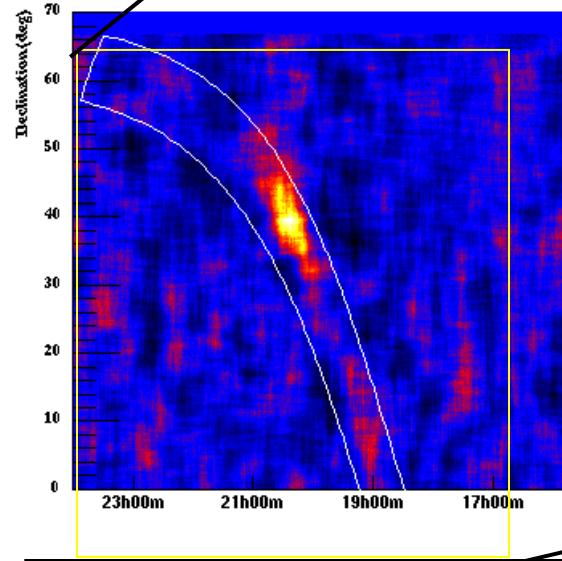
Galactic longitude 20-100 includes Cygnus region



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A Closer Look at the Galactic Plane

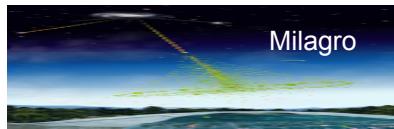
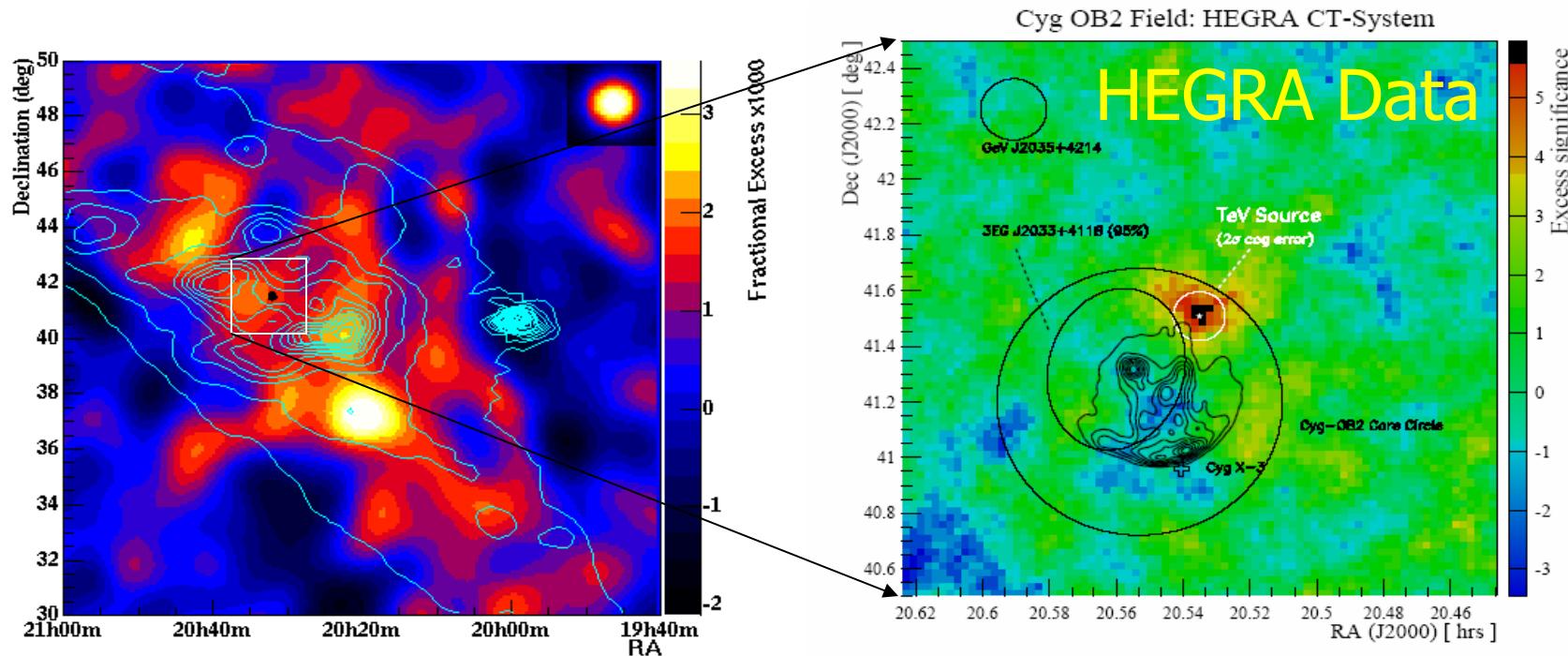
- GP diffuse excess clearly visible from $|l|=25^\circ$ to $|l|=90^\circ$
- Cygnus Region shows extended excess $\sim 5^\circ - 10^\circ$
- $F_{\text{Cygnus}} \approx 2x F_{\text{Crab}}$



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HEGRA Unidentified TeV Point Source: TEV J2032+4130

- HEGRA detected a 30 mCrab source in the Cygnus region
 - Milagro's point source sensitivity is insufficient to detect
 - The diffuse excess contributes a floor shift of ~1-2 mCrab to the HEGRA background
- Cygnus region is the most luminous TeV source in the northern sky, but a hard target for ACTs



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